Black hole binaries and light fields
Gravitational molecule

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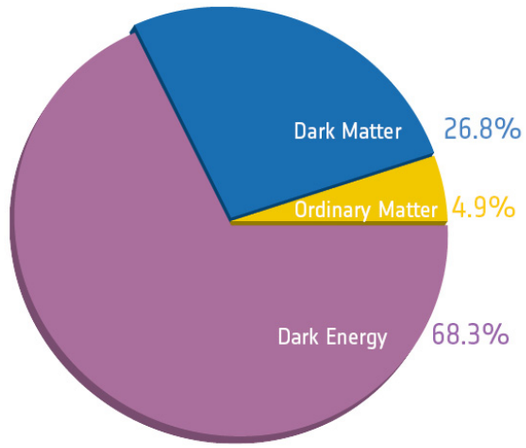
- *Phys.Rev.D* 103 (2021) 2, 024020. T.I, L.Bernard, V.Cardoso, M.Zilhao

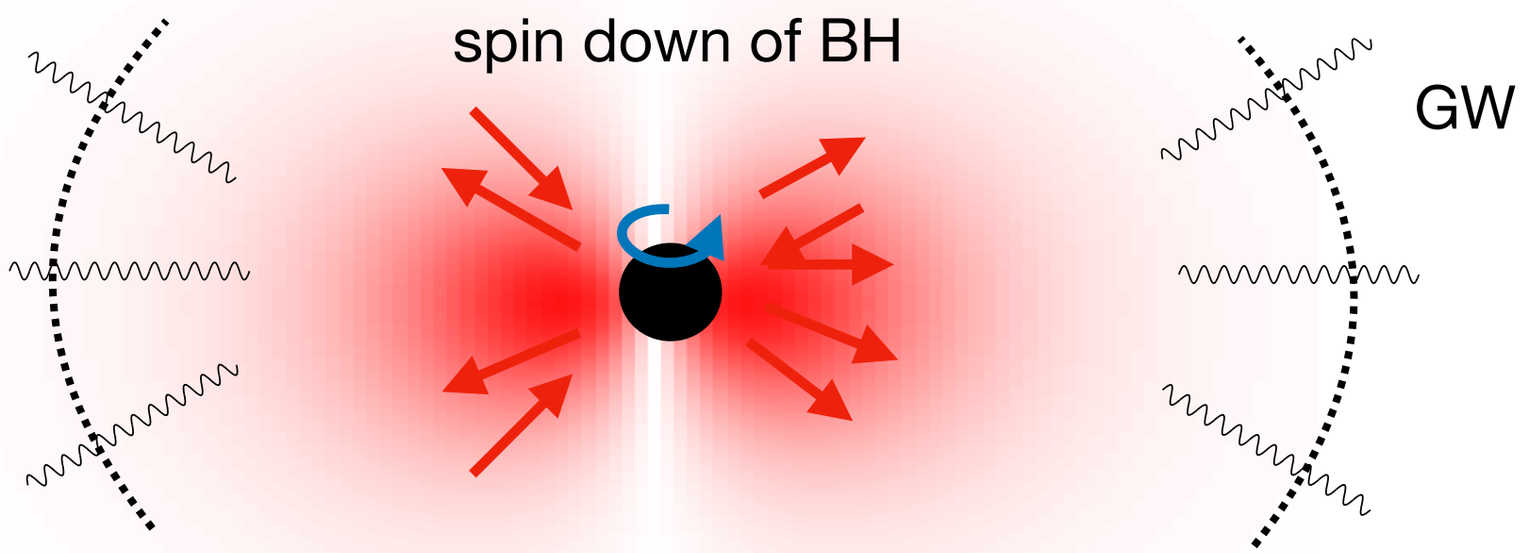
BHs as particle detectors

- New physics ?
  - axion, axion-like particle ? see. Arvanitaki et.al (2015)
  - light vector field, dark photon ?
  - light tensor field ? cf:massive gravity, bigravity
- BHs are useful tools for searching new particles.



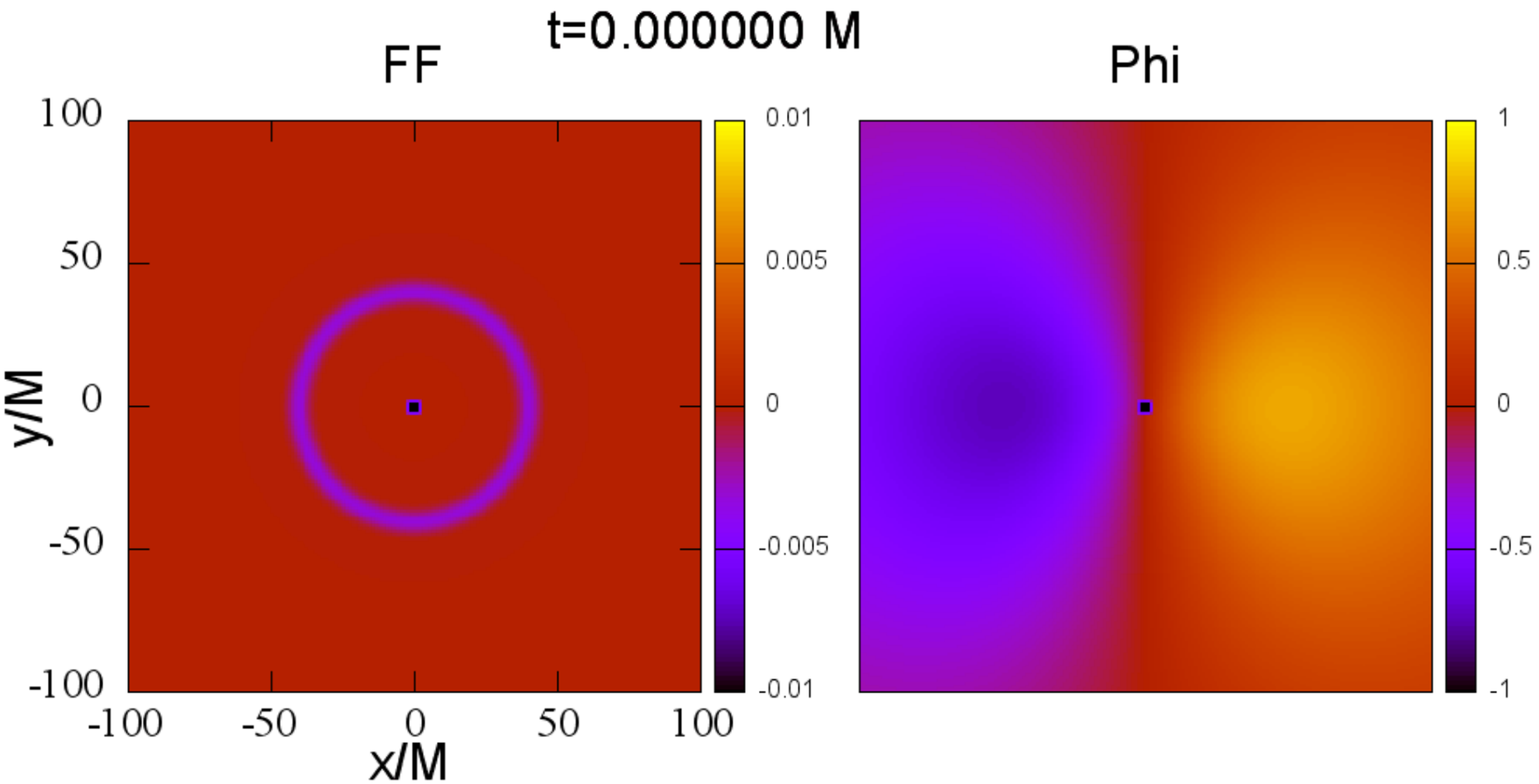
  - Superradiant instability

$$\tau \sim 100\tilde{a}\left(\frac{10^6 M_\odot}{M}\right)^8\left(\frac{10^{-16}\mathrm{eV}}{\mu}\right)^9 \mathrm{sec}$$



BHs as particle detector

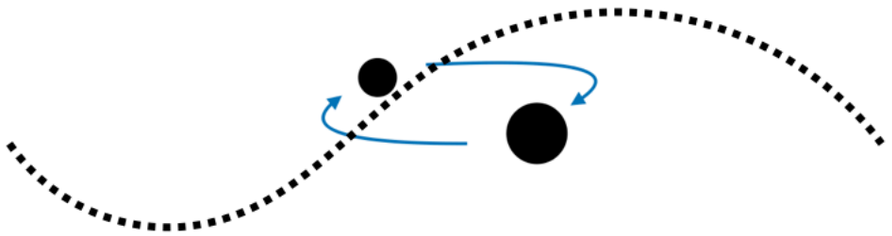
$$\begin{cases} (\nabla^2 - \mu^2)\Phi = \dfrac{k_{\mathrm{a}}}{2}\tilde{F}_{\mu\nu}F^{\mu\nu} \\ \nabla_\mu F^{\mu\nu} = 2k_{\mathrm{a}}\tilde{F}_{\nu\mu}\nabla^\mu\Phi \end{cases}$$



Phys.Rev.D 99 (2019) M.Boskovic et al
Phys.Rev.Lett. 122 (2019) 8, 081101 T.I et al

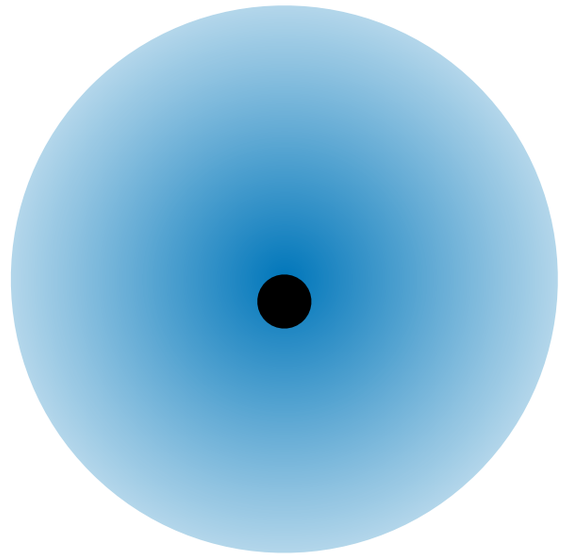
BHs as particle detectors

- We can imagine several situations in which BHs interact with light field as an environment.



Binary black hole in scalar field
What is typical state ?

Gravitational molecule



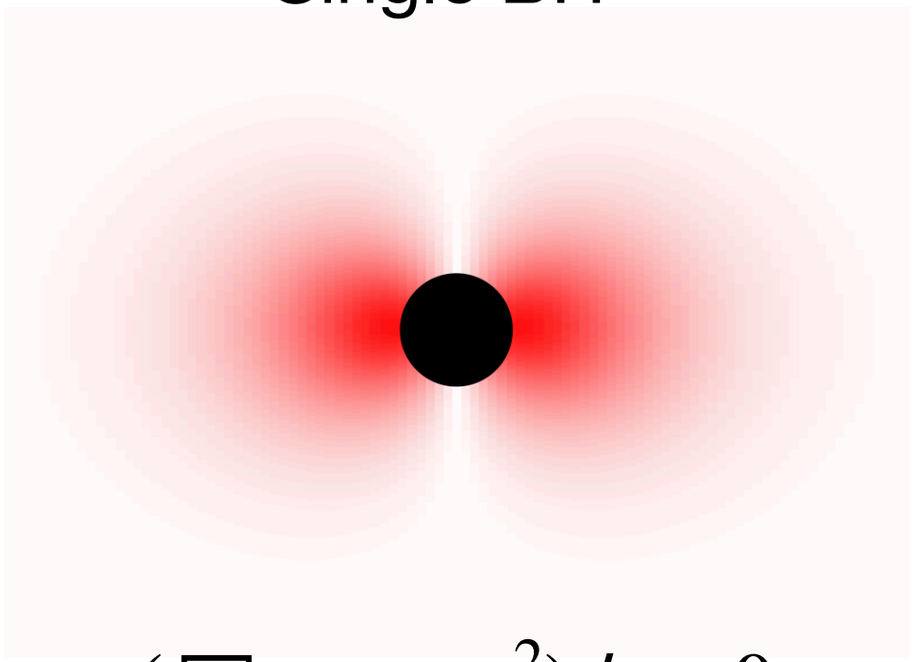
Black hole in dark matter halo
accretion of BS by BH ?
but what is the process, and time scale ?

cf : arXiv:2207.XXXX
V.Cardoso, TI, R.Vicente, M.Zilhao

atom vs molecule

$$\phi = \frac{1}{\sqrt{2\mu}}\left(\varphi e^{-i\mu t} + \mathrm{c.c.}\right)$$

Single BH



$$(\Box_{\mathrm{Kerr}} - \mu^2)\phi = 0$$

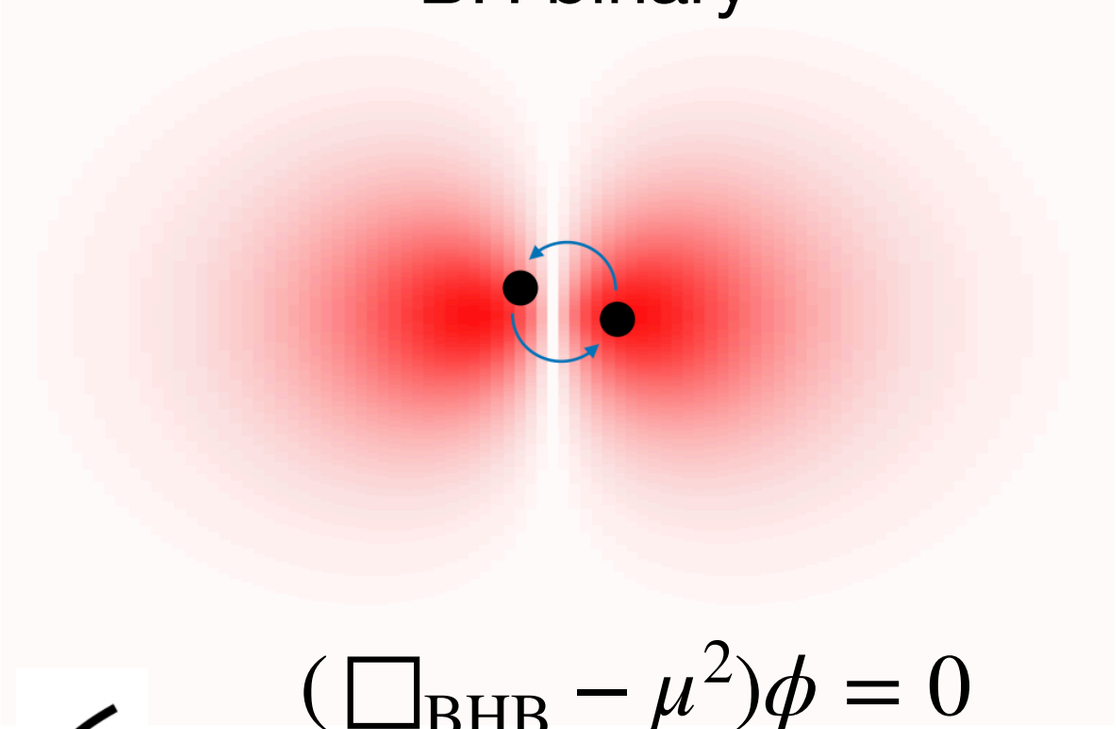
$$i\partial_t\varphi = \left(-\frac{1}{2\mu^2}\nabla^2 + V(r)\right)\varphi$$

$$V(r) = \frac{\mu M}{r}$$

Hydrogen atom : $|n, l, m>$

Gravitational atom

BH binary



$$(\Box_{\mathrm{BHB}} - \mu^2)\phi = 0$$

$$i\partial_t\varphi = \left(-\frac{1}{2\mu^2}\nabla^2 + V(r)\right)\varphi$$

$$V(r) = \frac{\mu M_1}{|r - r_1(t)|} + \frac{\mu M_2}{|r - r_2(t)|}$$

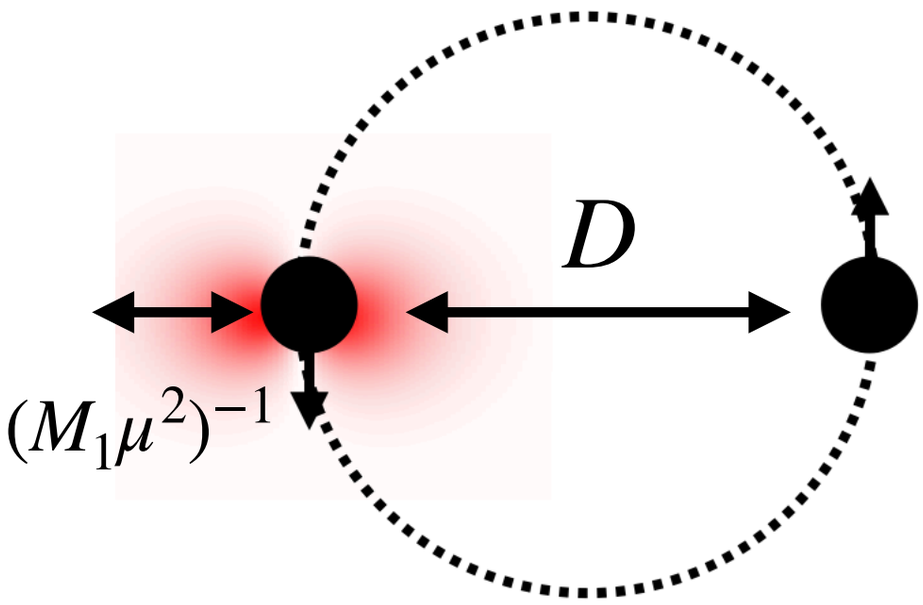
Di-hydrogen molecule

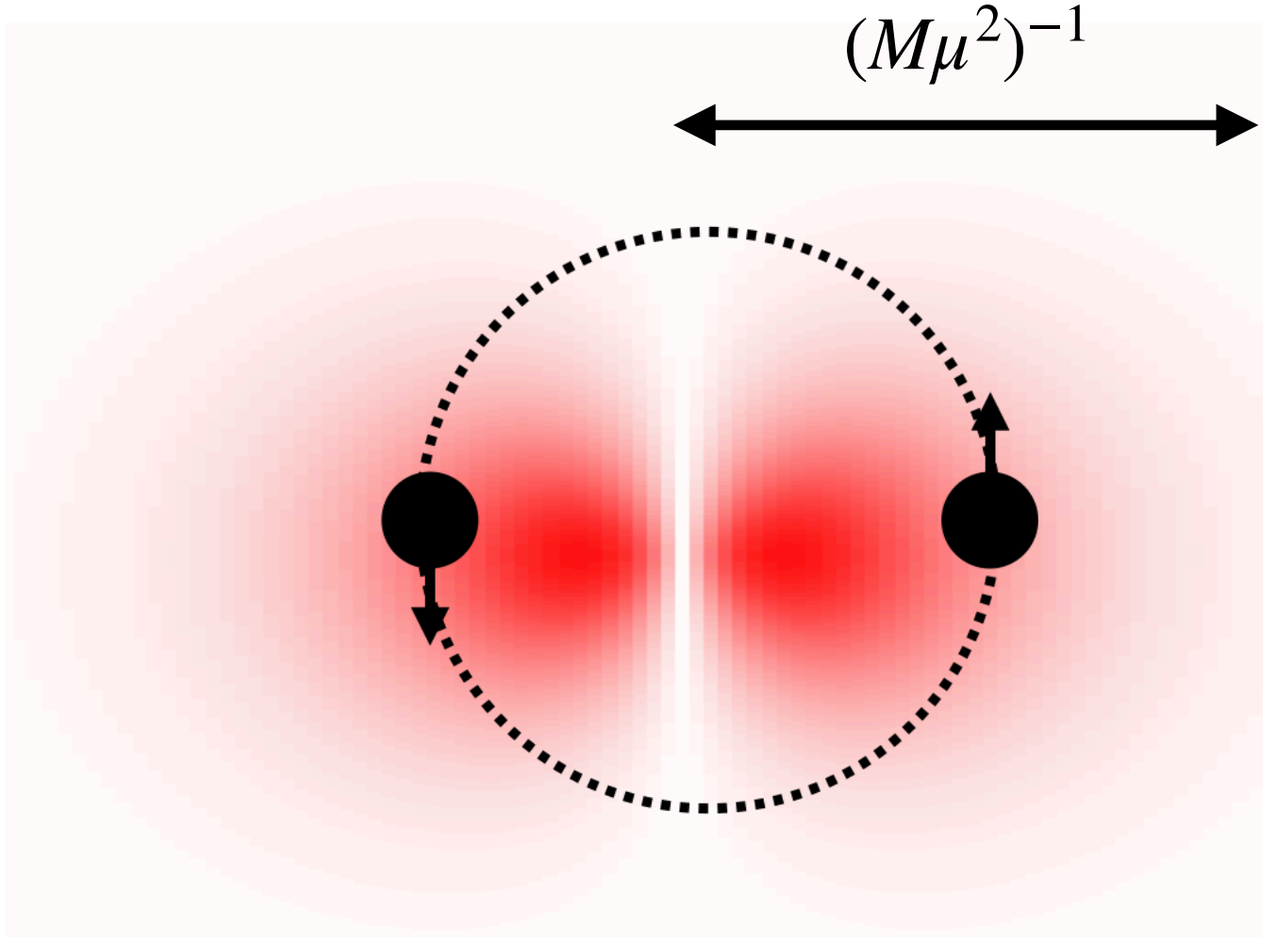
Gravitational molecule

Typical length scale

$$\left(\Box - \mu^2\right)\phi = 0$$

$$M_1 = M_2 = \frac{M}{2}$$





$\mathcal{O}\left((M_1\mu^2)^{-1}\right) \ll D$: gravitational atom around individual BH

$\mathcal{O}\left((M\mu^2)^{-1}\right) \gtrsim D$: gravitational molecule around BH binary

Initial data

- We evolve the test massive scalar field around binary BH.
- Initial data.

$$\phi = R(r)\mathscr{A}(t,\theta,\varphi)$$

$$\begin{cases} \phi = Ae^{-\frac{1}{2}\left(\frac{r}{w}\right)^2} \\ (\partial_t - \mathscr{L}_\beta)\phi = 0 \end{cases}$$

$$\begin{cases} R = A_0 r e^{-\frac{r}{2w}} \\ \mathscr{A} = \mathrm{Re}\left(Y_{1,1}(\theta,\varphi)\ e^{-i\mu t}\right) \end{cases}$$

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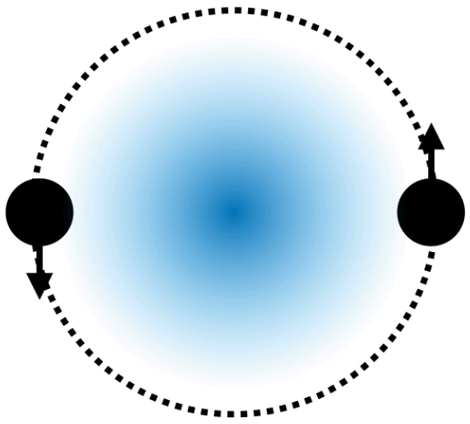
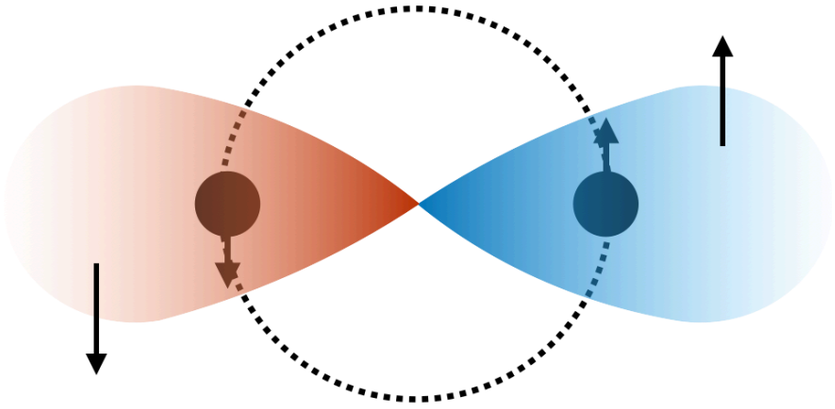
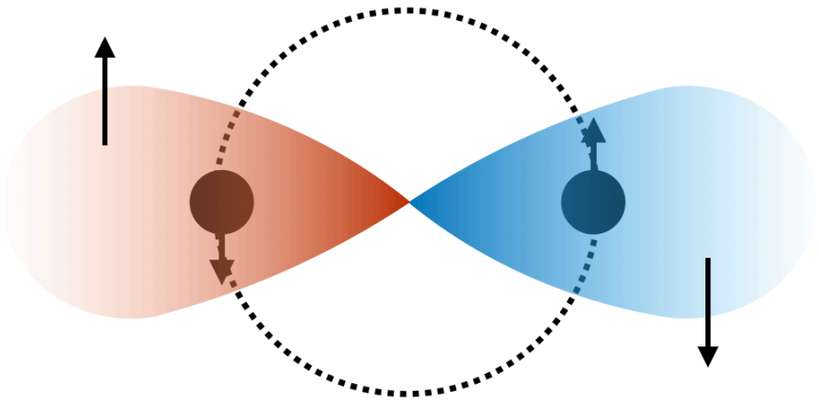


Gaussian profile



Co-rotating dipole



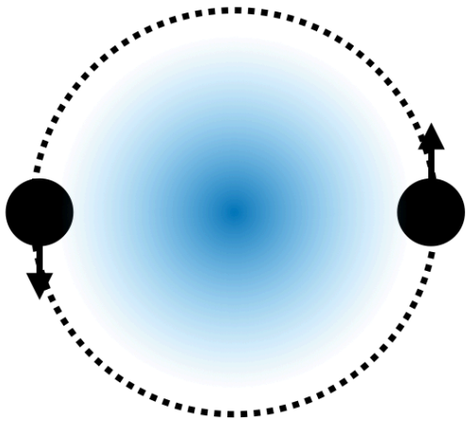
Counter-rotating dipole

Initial data

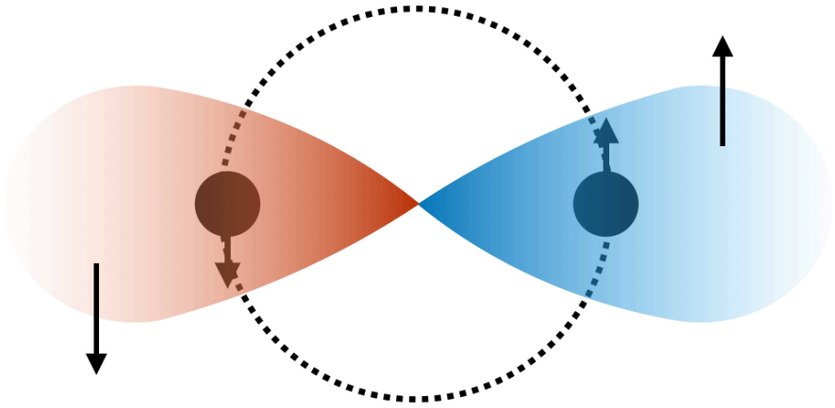
- We evolve the test massive scalar field around binary BH.
- Initial data.

$$\phi = R(r)\mathscr{A}(t,\theta,\varphi)$$

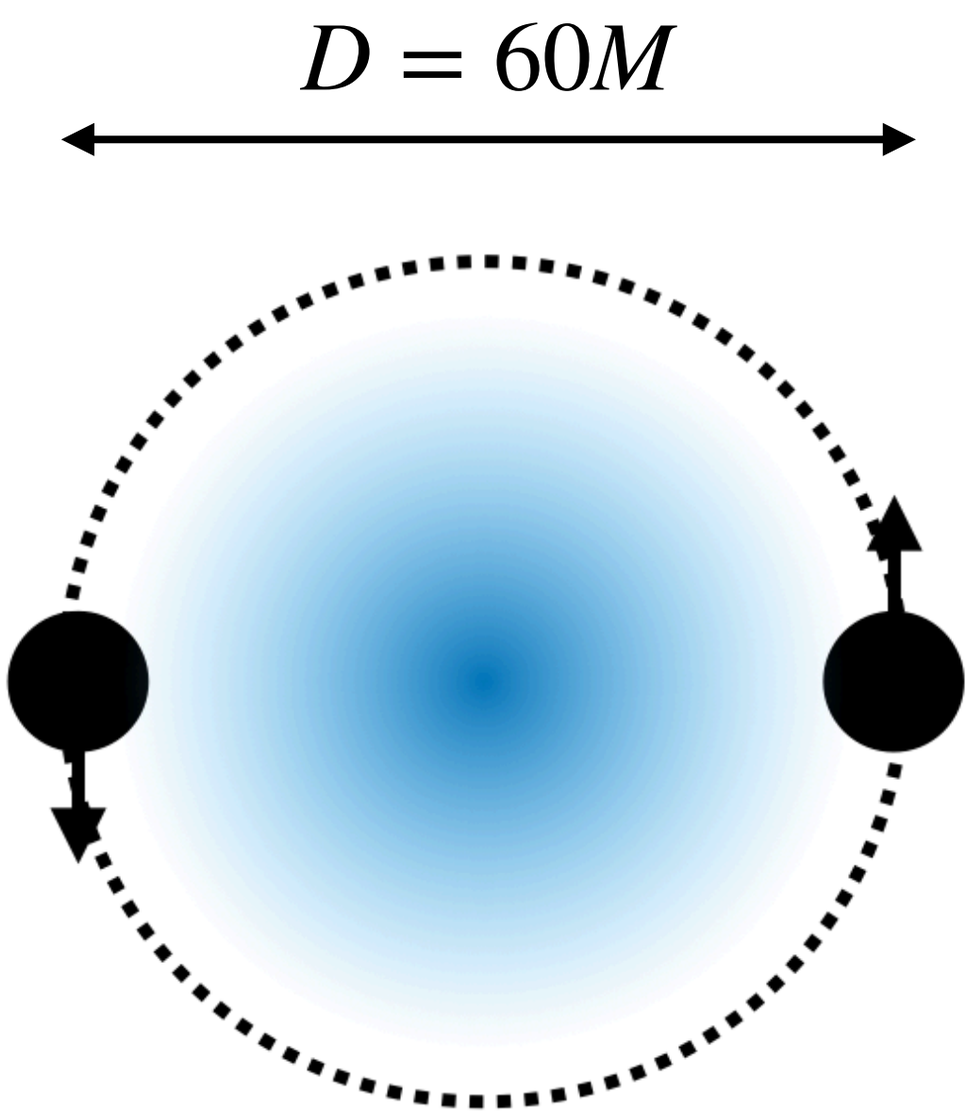
$$\begin{cases} \phi = Ae^{-\frac{1}{2}\left(\frac{r}{w}\right)^2} \\ (\partial_t - \mathscr{L}_\beta)\phi = 0 \end{cases} \qquad \begin{cases} R = A_0 r e^{-\frac{r}{2w}} \\ \mathscr{A} = \mathrm{Re}\left(Y_{1,1}(\theta,\varphi)\, e^{-i\mu t}\right) \end{cases} \qquad \begin{cases} R = A_0 r e^{-\frac{r}{2w}} \end{cases}$$



Gaussian profile



Co-rotating dipole



$$\mu M = 0.5$$

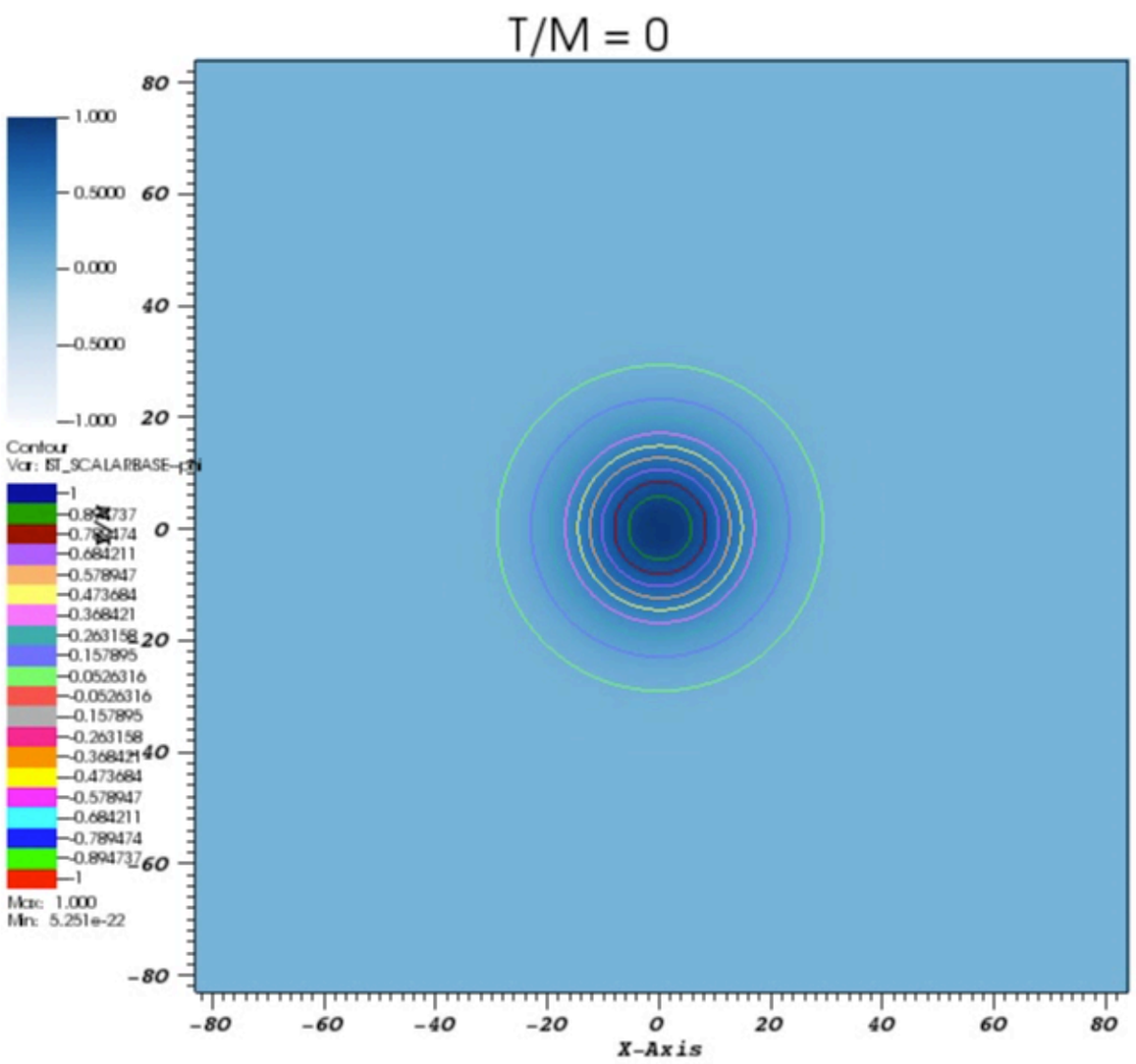
$$w = 25M$$

$$\mathcal{O}\left((M_1\mu^2)^{-1}\right) \ll D$$

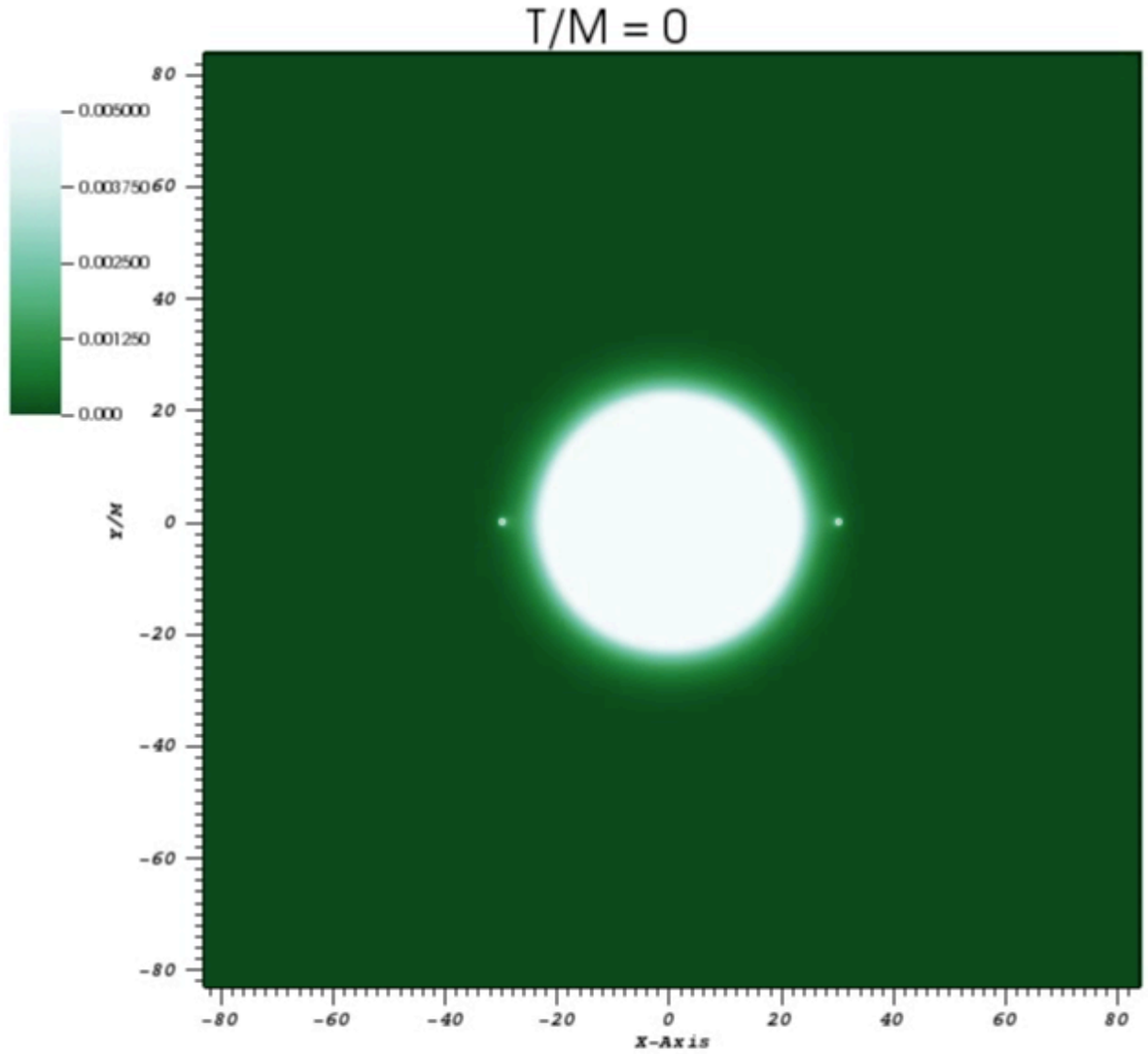
Simulation 1 : Gaussian initial data

Simulation 1

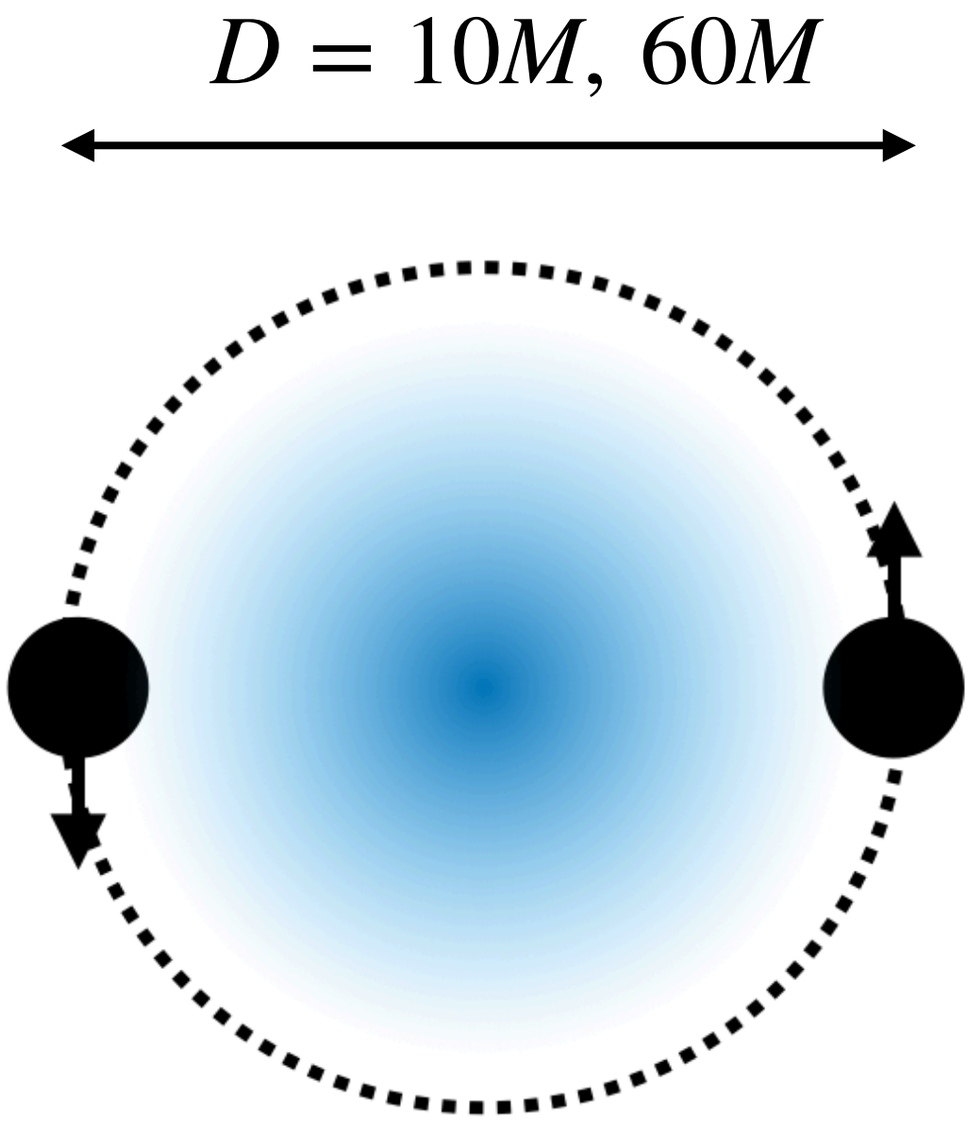
Scalar field



Energy density



- Gravitational atom around individual BHs.



$$\mu M = 0.2$$

$$w = 25M$$

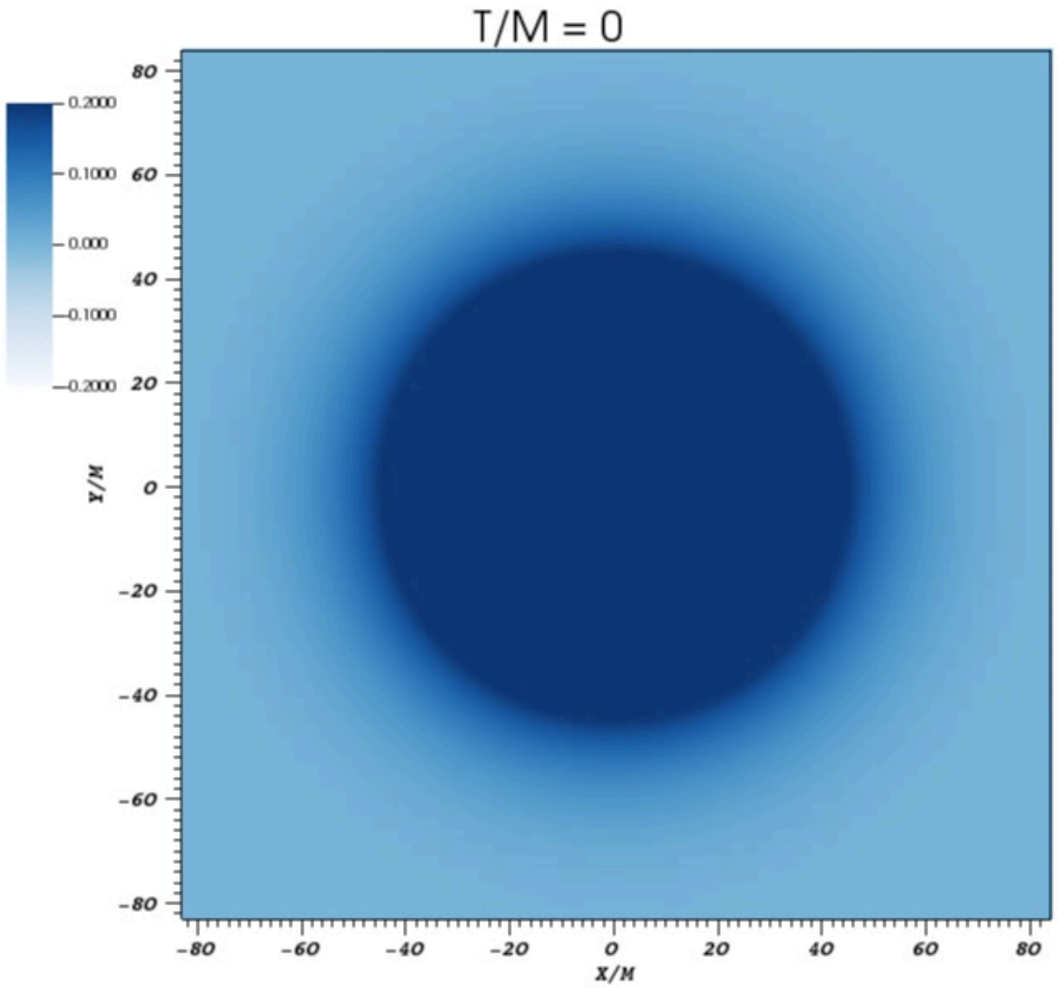
$$\mathcal{O}\left((M\mu^2)^{-1}\right) \gtrsim D$$

Simulation 2 : Gaussian initial data

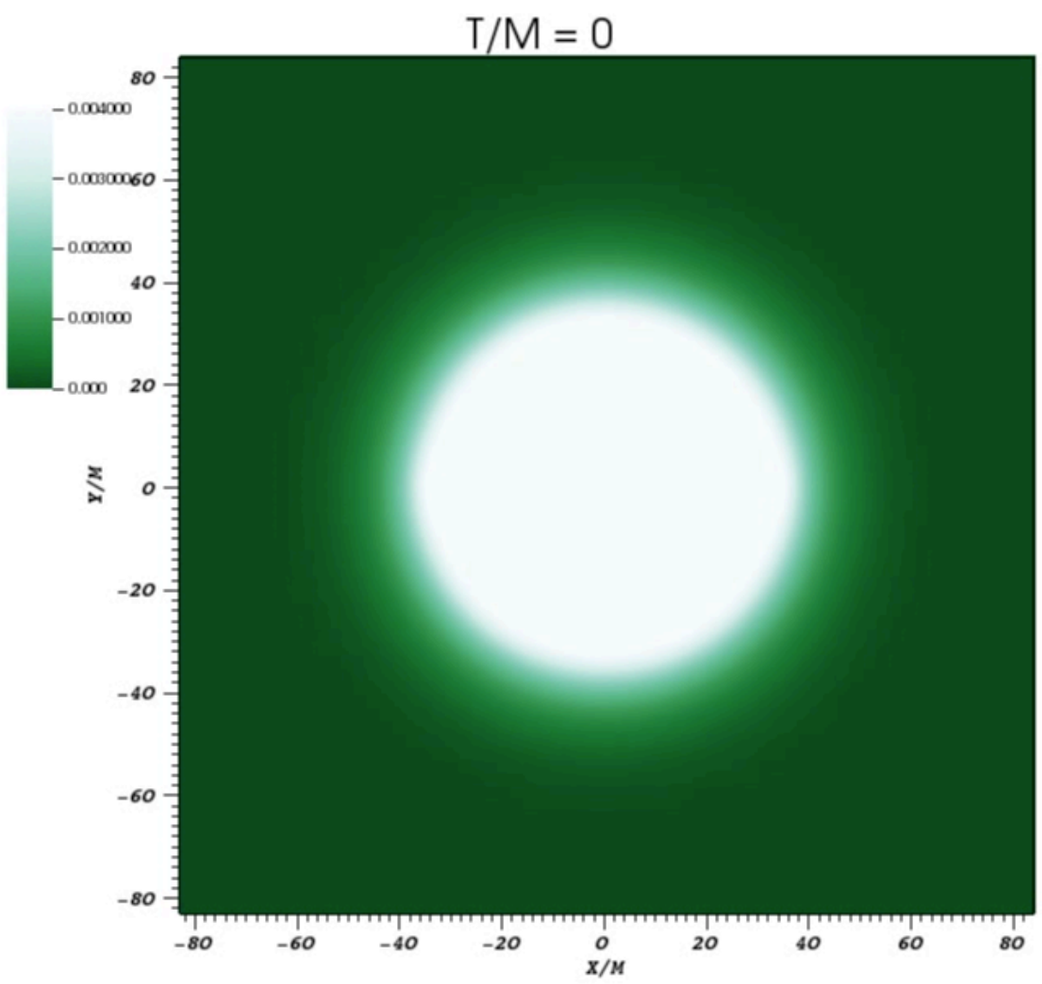
Simulation 2

$$D = 60M$$

Scalar field



Energy density

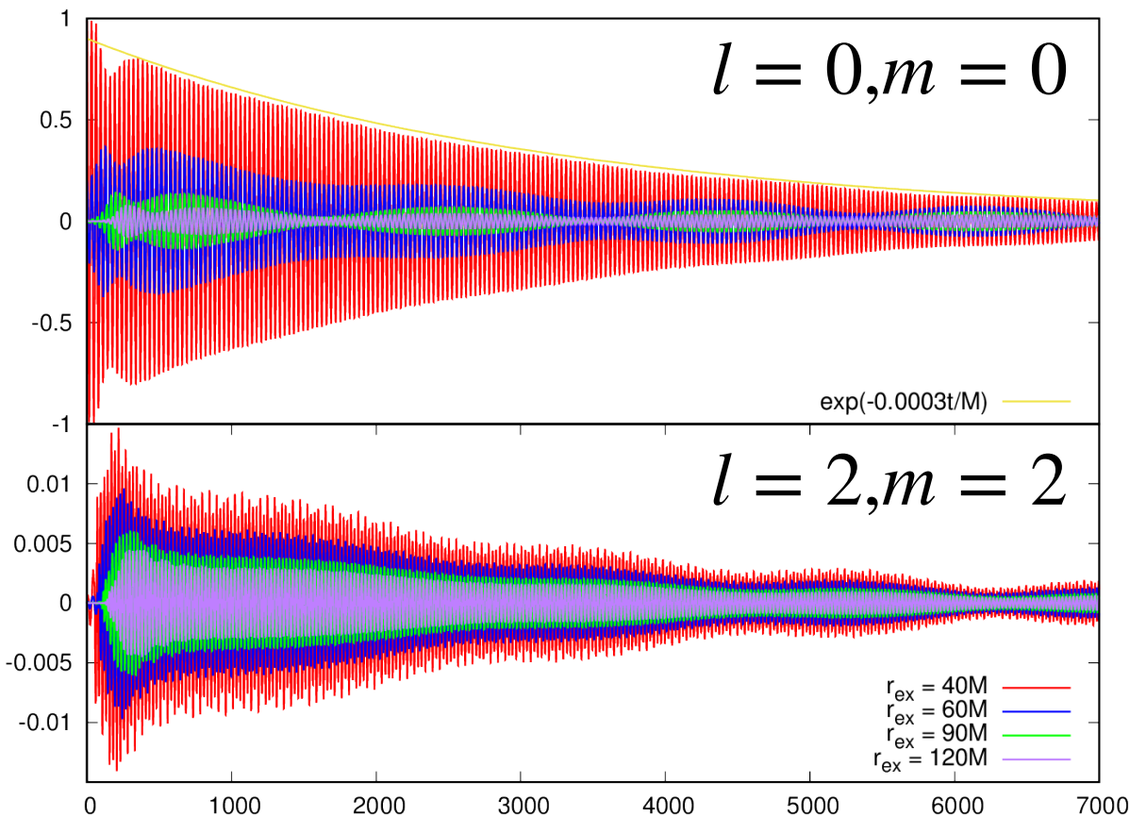


- “Monopole” gravitational molecule around BH binary.
- We checked the spectrum is similar to Di-hyrogen molecule.

Simulation 2

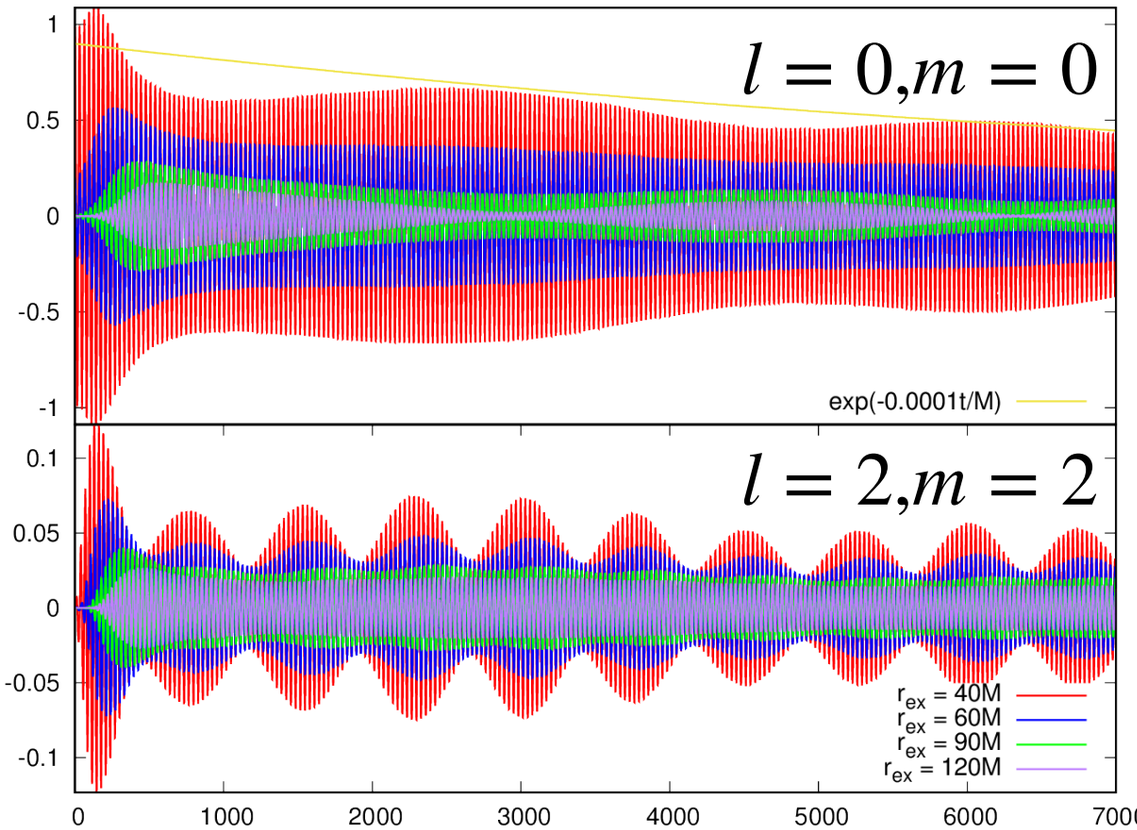
cf: $\phi_{00} \sim e^{-\frac{t}{\tau}}$

$D = 10M$



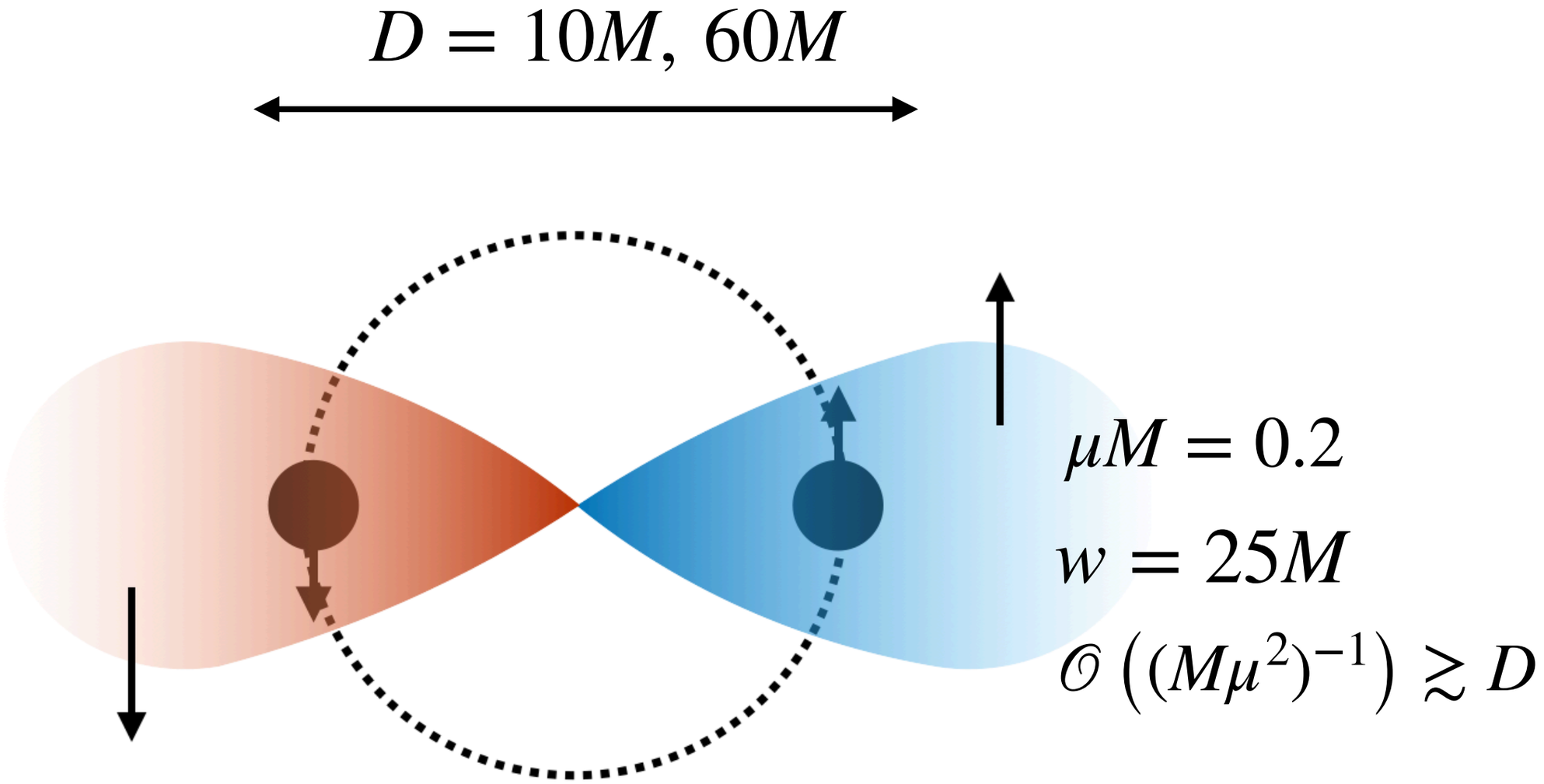
$\tau \simeq 3 \times 10^3 M$

$D = 60M$



$\tau \simeq 1 \times 10^4 M$

- The spectrum of numerical simulation is good agreement with Di-hydrogen molecule.

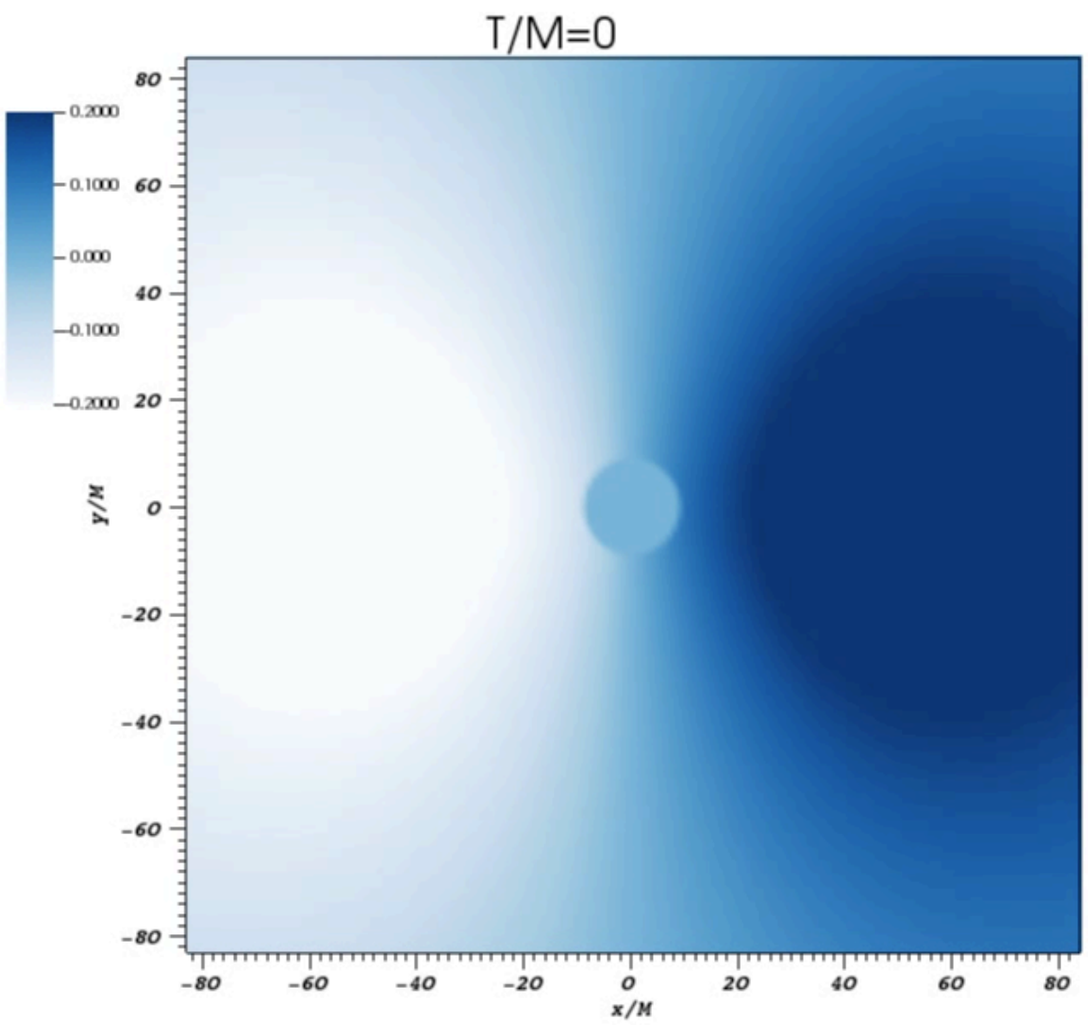


Simulation 3 :
Co-rotating dipole initial data

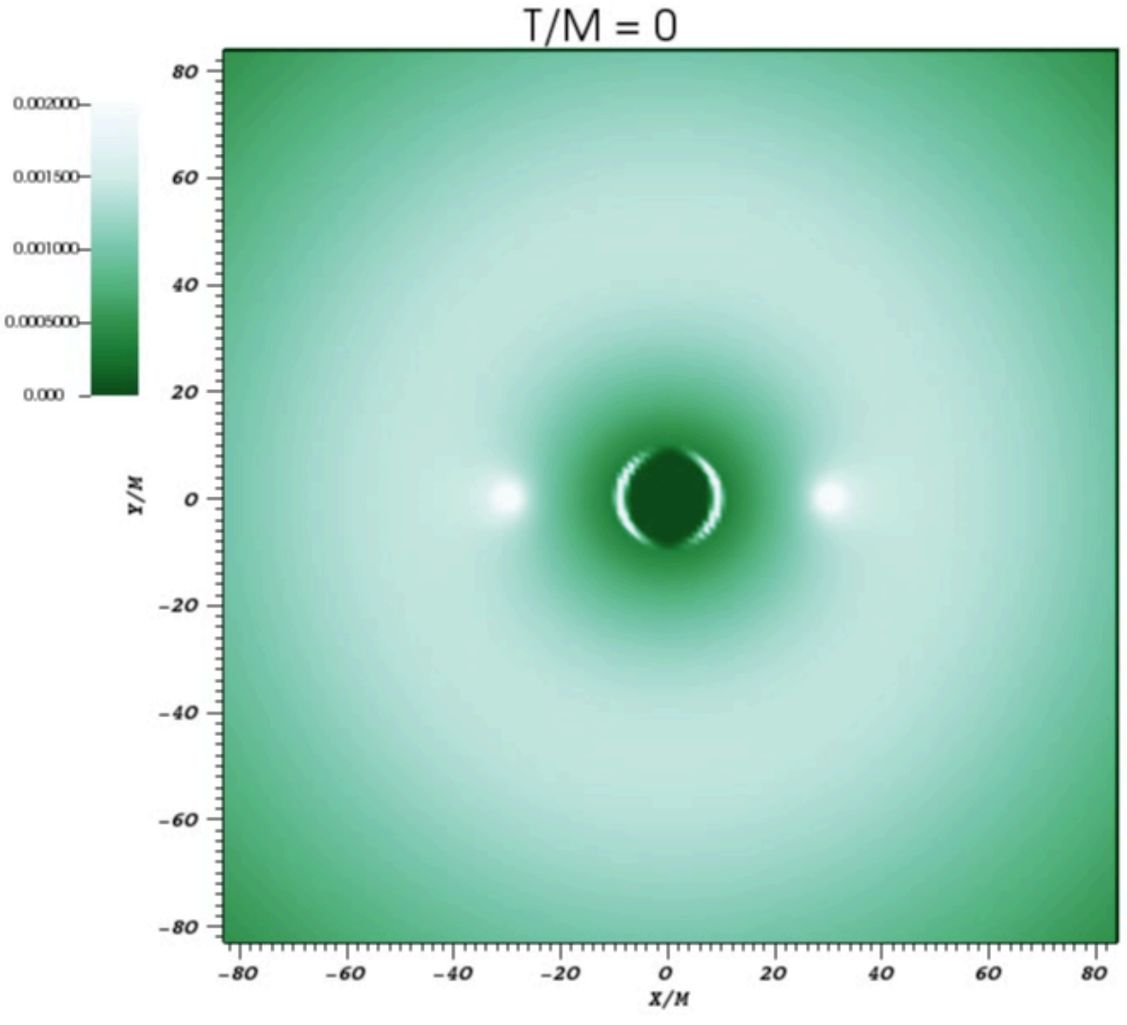
Simulation 3

$$D = 60M$$

Scalar field



Energy density

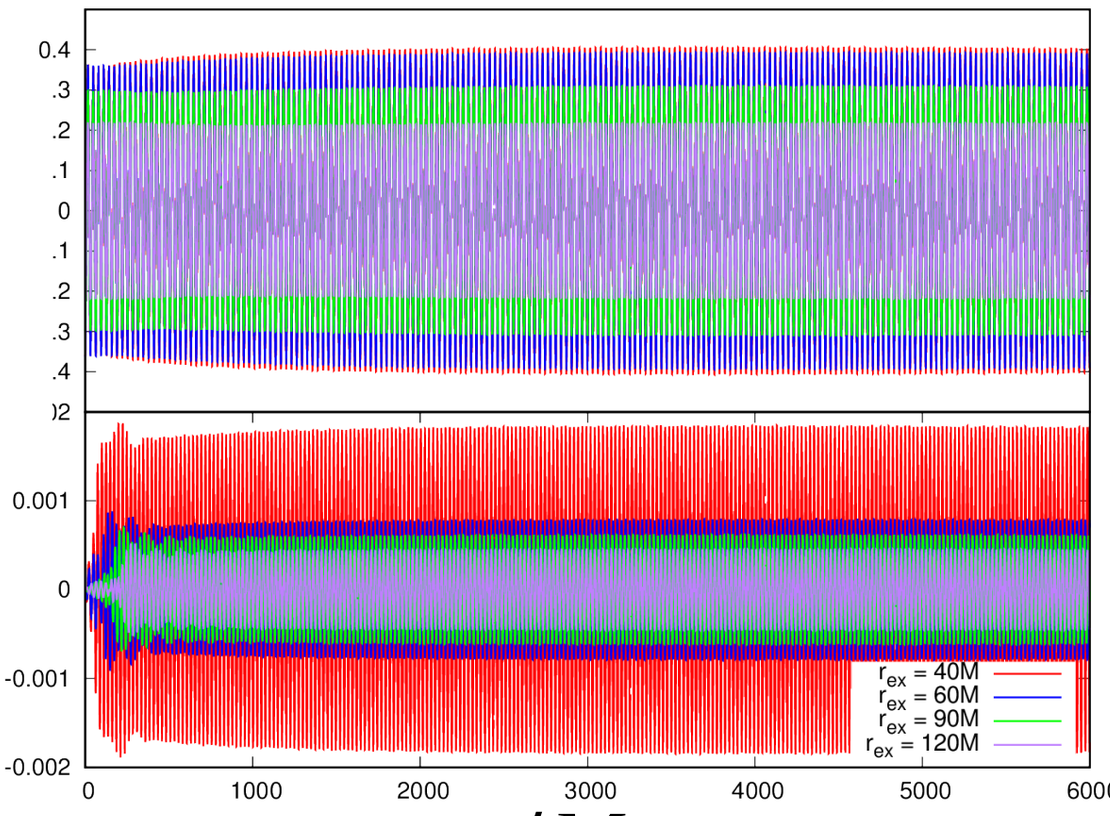


- Energy density rotates with binary.
- “Dipole” co-rotating gravitational molecule around BH binary.

Simulation 3

$D = 10M$

$l = 1, m = 1$

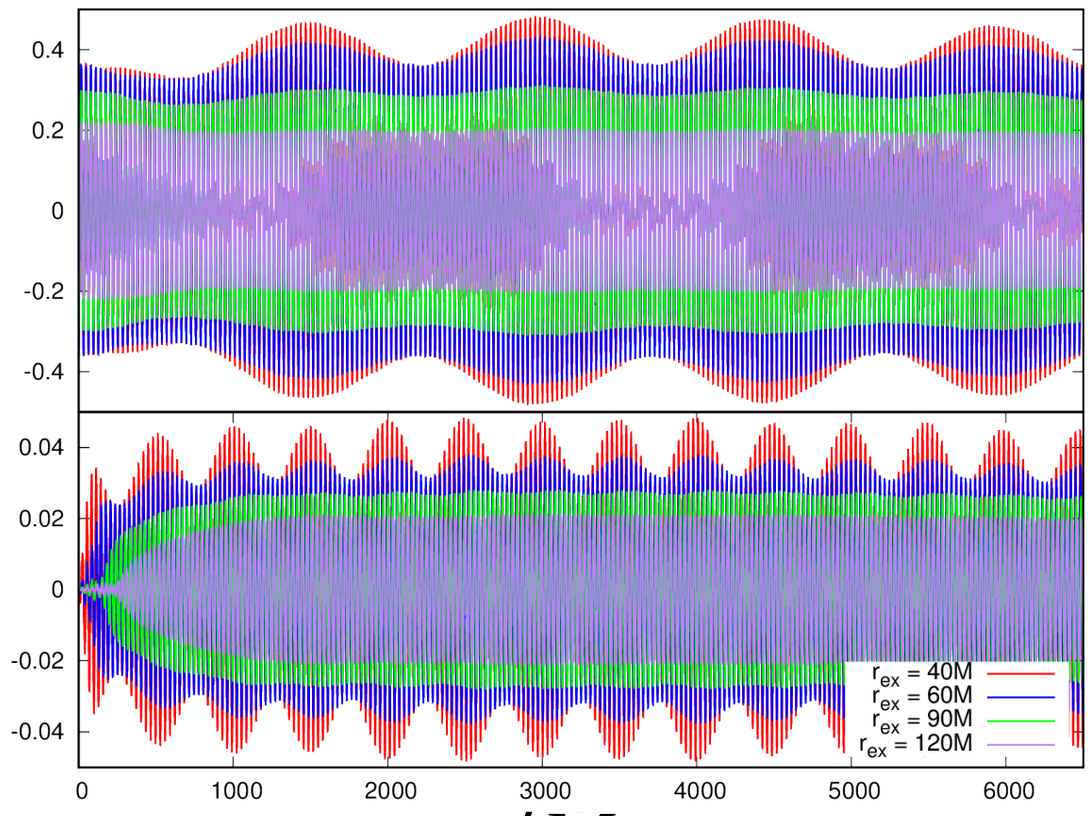


t/M

$l = 3, m = 3$

$D = 60M$

$l = 1, m = 1$



t/M

$l = 3, m = 3$

We could not get decaying time scale.

At least, $\tau \gg 10^4 M$. This is long-lived bound state.

Summary

- Our result
  - Strong evidence for existence of global bound state (Gravitational molecule).
  - Analogy with QM of di-hydrogen atom.
- Future works
  - eccentricity orbit ?
  - Gravitational wave from the gravitational molecule ?
  - Force between BHs due to the molecule ?
  - Can we observe the force using GW from binary ?

Finish